EFFECT OF BLOCKAGE RATIO ON BISTABILITY PHENOMENON OF THE FLOW ON TWO CIRCULAR CYLINDERS SIDE-BY-SIDE

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Abstract. *This paper presents an experimental study of the effect of blockage ratio in an aerodynamic channel on the bistability phenomenon that occur when the wakes of two cylinders placed side by side are deviated to the back side of one or the other cylinder, assuming a stable characteristic for a certain period of time. The blockage ratio in the channel was varied by means of cylinders of different diameters. Two different pitch-to-diameter ratios were studied (p/d = 1.26 and 1.6). The experimental technique consists of measuring velocity fluctuations in aerodynamic channel using the hot-wire anemometry technique. The Reynolds number of this experiment varies between 3,720 to 76,100 and the blockage ratio from 4.66 to 62.18%. Experimental data from the aerodynamic channel are treated with the use of statistical tools, spectral and wavelet analysis. The results show the influence of blockage ratio on the bistability phenomenon, being more prevalent for the arrangement with p/d=1.6. For higher blockage ratios, the bistability phenomenon may not occur or occurs for short periods of time. For lower blockage ratios, since the tubes have smaller diameters, the phenomenon does not occur or could not be captured with the experimental technique employed.*

Keywords: *turbulent flow, hot-wire anemometry, bistability, blockage, wavelets.*

1. INTRODUCTION

Phenomena occurring in the flow around cylinders are part of a large group of engineering applications such as in shell and tube heat exchangers in chimneys groups, vertical cylinders on ships rotors, electricity transmission lines, among others. The behavior of such phenomena has direct influence in project development, particularly as regards the behavior of vortex shedding and fluid-structure interaction. One of the parameters involved in this kind of study is the blockage ratio.

The turbulent flow on circular cylinders placed side-by-side presents a floppy and random phenomenon that changes the flow mode. This behavior is called in the literature as bistable flow and is characterized by a wide near-wake behind one of the cylinders and a narrow near-wake behind the other.

In the study of the effect in aerodynamic channel, the blockage ratio is given by *d/L*, where “d” is the diameter of the cylinder and “L” the channel width. Maskell (1963) proposes a method for analyzing the blockage effects of wind tunnel for bluff bodies based on the balance of momentum and the idea that the increase in the wall effects on tunnel leads to a simple increase in the velocity of the undisturbed flow.

Works like as West and Apelt (1982), which involves the blockage effect on flow around circular cylinders, where blockage ratio between 6 and 16% cause changes in pressure distribution and increase of the Strouhal number, a range number between Reynolds 10^4 e 10^5. Anagnostopoulos et al. (1996) conducted a numerical study of the blockage effect on circular cylinders in permanent and transient flows with Re = 106 and ratios of 5%, 15% and 25%. They showed that the hydrodynamic forces on the cylinder and Strouhal number increase with increasing ratio.

A classification of blockage effects of the flow in circular cylinders was made by Zdravkovich (2003):

***d/L* < 10%**: The the blockage effect is small and can be ignored;

10% < *d/L* < 60%: Blockage changes the flow, corrections in the measured data is necessary;

***d/L* > 60%**: Blockage radically alters the flow around the cylinder, and corrections in the data make no sense.

More recently, Indrusiak and Möller (2011) performed measurements in the wake of behind a cylinder submitted to nonstationary impinging flow. The results are complementary to those of West and Apelt (1982) showing that, for blockage ratio of 16.5% and Re < 2.5 × 104, the Strouhal numbers are strongly affected by the deviation of the flow around the cylinder and experience an increment of as large as 57% at lower Reynolds numbers.

For two cylinders, Zdravkovich (1977) conducted a study where it was found in the flow on two cylinders arranged side-by-side two different drag coefficients and base pressure fluctuation between two extreme values. The Author associates a resultant force that acts perpendicular to the main stream to a lift force on the deviated flow.

This paper presents the study of the effect of blockage ratio on the Strouhal number of the wake behind single cylinders. The effect on the bistability phenomenon for two cylinders placed side-by-side is also studied.

2. BISTABLE PHENOMENON

According to Sumner et al. (1999), the cross steady flow through circular cylinders of same diameter (d) placed side-by-side presents a wake with different modes depending on distance between the centers of the cylinders (p).

In intermediate spacing ratios (1.2 < p/d < 2.2) identifies the flow to form two wakes behind the cylinders, a large wake behind a cylinder and a narrow belt after another, Figure. 1. The presence of these wakes make two dominant frequency vortex shedding are derived: one related to the higher narrow wake, and another is associated with lower wide wake. The flow passing through the slit is deviated toward the wake narrower. The bistable phenomenon called, according to the technical literature, the flow pattern undergoes a change that deviated intermittent, sometimes oriented toward a cylinder, sometimes in the other direction. This phenomenon is considered an intrinsic property of the flow and is independent of Reynolds number and is not related to misalignments between the cylinders or any other external influence.

According to Kim and Durbim (1988), the transition between two asymmetric states is random, being the time scale between transitions about 10^3 times larger than the period vortex shedding, while for Peschard and Le Gal (1996), the behavior is not intrinsic to the flow, but disturbances associated with turbulent flow at the entrance.

Guillaume and LaRue (1999) define terms that describe each of the three types of bistable behavior, the ***quasi-stable behavior*** where the flow does not vary with time and large-scale disturbances can cause changes in the average values of the wakes, but the new values remain the same until another major disturbance is applied; the ***spontaneous flopping***, where the average flow observed over time alternate between a high value and one featuring the two modes flow, even if no disturbance is applied; and the ***forced flopping***, exchanges that are derived a large disturbance applied.

Sumner et al. (1999) conducted a study of flow around two and three cylinders arranged side-by-side across the flow, for pitch ratios between 1 and 6 and Reynolds number in the range between 500 and 3000. In the experiment for two cylinders, was not identified the bistable phenomenon. The non appearance of bistability was attributed to the combined effects of the small degree of misalignment of the cylinders and experimental effects such as and aspect and blockage ratios, the latter being 13%.

Zhou et al. (2002) studied about the turbulent on wake two cylinders placed side-by-side in terms of velocity fields and temperature, for the pitch ratios p/d between 1.5 and 3.0. The results were compared with the wake of a single cylinder. The authors attributed the extreme narrowing of the gap, the fact that only one frequency, not two, be measured. A gap between the cylinders very close can inhibit the generation of vortices behind the cylinders, and start to act as one body with only one wake vortex generated.

For Alam et al. (2003) the flow around two circular cylinders of equal diameter, arranged side-by-side in the transverse direction of the flow shows that the wake vortices have different modes of flow. These studies were developed using the Reynolds number in the subcritical regime, 5.5 x 10^4 and, according to the authors, the forces exerted on the body are insensitive against variations of Reynolds number in this regime.

Alam e Zhou (2007) analyze the flow around two cylinders placed side-by-side on the cross-flow, for small pitch ratios (1.1 < p/d < 1.2), with a Reynolds number of 4.7 x 10^4. The authors identified four distinct modes flow.

Olinto et al. (2009) conducted a study of the bistable phenomenon in flow in aerodynamic channel on two cylinders arranged side-by-side, with Re = 3 x 10^4 and blockage rartio 33%. The author found the strong presence of bistability in measurements near to the cylinders (until x/d = 0,93), where "x" is the distance of the probe to the center of the cylinders. For a greater ratio distance did not identify the bistable standard.

De Paula (2008) studied the presence of the bistable phenomenon for two tubes, for pitch ratios p/d = 1.26 and 1.6, and Reynolds number range of 1.85 x 10^4 and 2.98 x 10^4. Several changes of velocity were observed during the entire period of data acquisition.

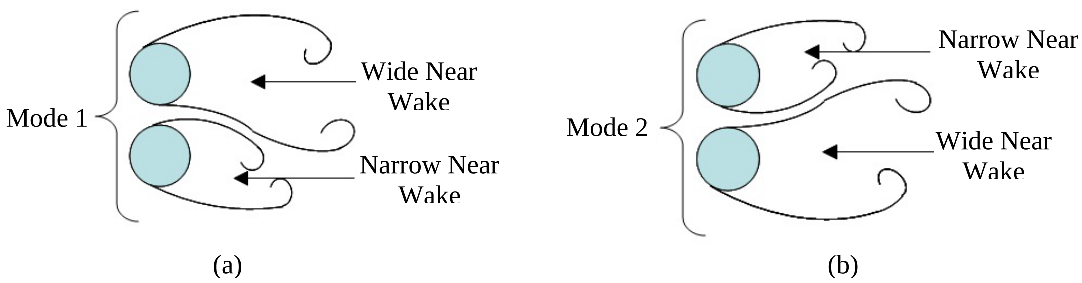


Figure 1. Bistability scheme for (a) mode 1 and (b) mode 2.

3. EXPERIMENTAL TECHNIQUE

To develop this study we used an aerodynamic channel that has a rectangular test section with internal dimensions 193 mm wide (W) by 146 mm high (H) and is represented in Figure 2(a). A 0.75 kW centrifugal fan drives the air through a diffuser, a grid, a honeycomb and two screens, which reduce the turbulence intensity in the channel about 1%.

To measure the velocity reference is used a Pitot tube fixed before the test section. The flow velocity in the aerodynamic is controlled from 0 to 15 m/s by means of a frequency inverter. Measurements were made with a flow velocity of 15 m/s for this analysis.

For the measurement of velocity fluctuations of the flow, constant temperature hot wire anemometry is used by means of a DANTEC *StreamLine*. Two single hot wire probes are positioned as shown in Figure 2(b) and 2(c), where the distance "x" of the probes to the cylinders is variable according to diameter of the tube examined. Data acquisition is done through a board A/D converter, NATIONAL INSTRUMENTS 9215 model, connected with USB interface and controlled by a personal computer. The software used for adjusting and configuration parameters of the probe and for data acquisition is *StreamWare* 3.4, also from DANTEC.

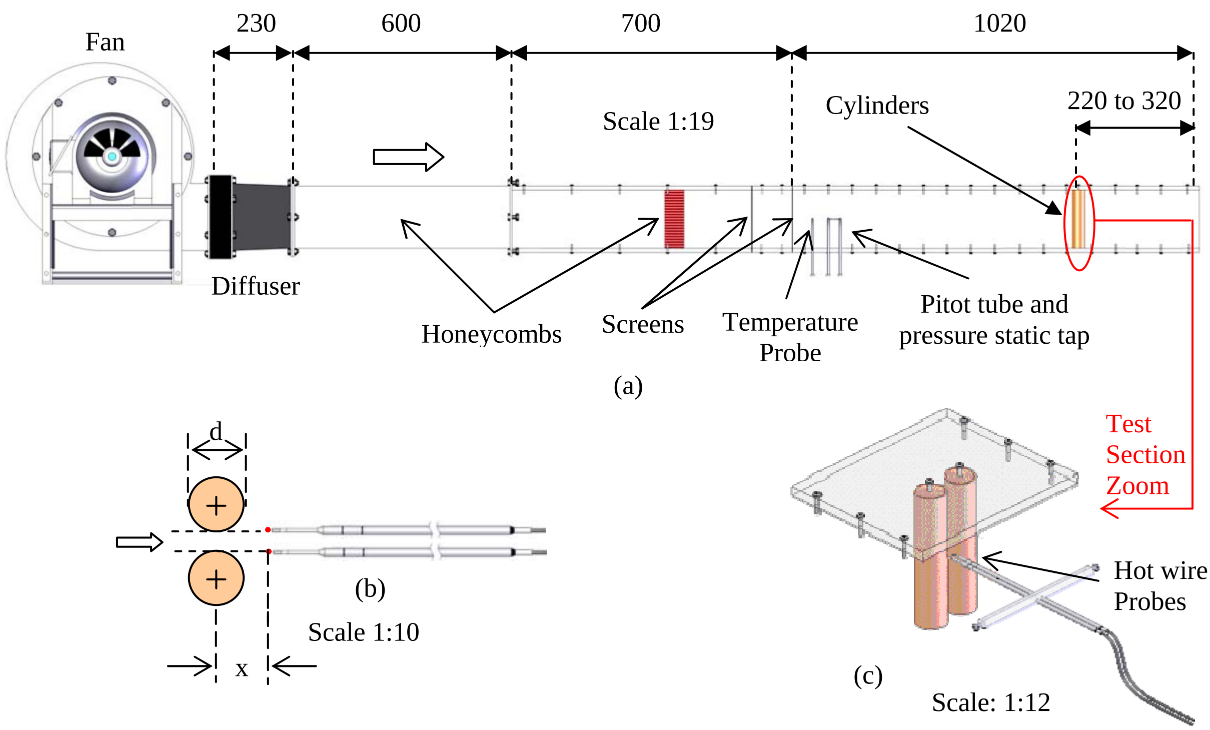


Figure 2. Schematic view of (a) the aerodynamic channel, (b) probes positions and (c) test section.

4. MATHEMATICAL TOOLS

For the analysis of the time series, the Fourier and wavelet transforms were used. Wavelets can localize the bistable phenomenon in time and frequency domain. Continuous and discrete wavelet transforms are used in this study. The mathematical analysis was made with Matlab 5.3 software using the toolboxes for the signals, statistical, spectral and wavelet analysis.

4.1. Fourier Analysis

For the processing of time-series data was made of Fourier transform and the Fourier spectrum, with the aim of obtaining a frequency domain analysis. Is used to account power spectral density function, which according to Bendat and Piersol (1971), highlights the main characteristics of acquired signals, consisting of the Fourier spectrum of a series, smoothed over all frequency ranges and on sets of estimates.

4.2. Wavelet Analysis

Wavelet functions have finite energy and zero mean, and are used for stationary and non-stationary signal analysis, Percival and Walden (2000). The continuous wavelet transform is used to obtain the spectrograms, where the energy distribution of a signal is associated with each time scale (or frequency). The discrete wavelet transform is used for reconstruction of the velocity signals obtained, where an approximation is made and is coupled with all the details, which have lost information between two successive approximationsIn this paper, Db20 wavelet level 9 was used, a width of the frequency range is 0 to 2.93 Hz. A more detailed discussion of wavelet analysis is done in Indrusiak and Möller (2011).

5. RESULTS

In this study the flow for two cylinders side-by-side, pitch-to-diameter ratio p/d = 1.26 and p/d = 1.6, were used. "p" is the distance between the centers of two cylinders and “d” is the diameter. The chosen diameters ranging between 4.5 and 60 mm. In this configuration, the blockage ratio on the channel varies between 4.66 and 62.18%, as shown in Table 1. The Reynolds number on the aerodynamic channel varies from 3.72×10^3 to 7.61×10^4. These values are based on the average velocity of undisturbed flow (characteristic velocity) and the diameter of each cylinder (characteristic length).

Table 1 – Cylinders and their blockage ratio

Cylinders Diameter (mm)	Blockage Ratio
4.5	4.66 %
9.1	9.43 %
15	15.54 %
25	25.91 %
32	33.16 %
40	41.45 %
50	51.81 %
60	62.18 %

5.1. Results for p/d = 1.26

For this pitch-to-diameter ratio, the bistable phenomenon was not identified in the cylinders of diameters of 4.5, 9.1 and 15 mm. For cylinders of 4.5 mm in diameter, since each probe has a length of 1 mm, the probe size has the magnitude of the wake, making difficult the detection of the phenomenon. For cylinders diameters of 9.1 mm and 15 mm it is likely that the probes measured the velocity within the same wake, or just a wide wake due to the deviation of the flow through the gap between the tubes. However, in the case of the cylinders with 15 mm diameter and p/d-ratio of 1.6, the flow through the gap hindered the occurrence, or at least, the observation of the bistability.

The arrangement of cylinders with 32 mm did not show bistable characteristics and the argument for this is associated with the measurement of the velocity within the same wake and the strong dependence of the phenomenon with the positioning of the probe, which was derived from observing the best sign of turbulence arrangement identified by an oscilloscope. Table 2 shows the statistical characteristics for cylinders of 4.5, 9.1,15 and 32 mm.

The cylinders with 25, 40 and 50 mm showed the bistability phenomenon, as shown in Figure 3, where the number of changes decreases with the increase of the diameter. In Figure 3, with the cylinders of 60 mm, the measured velocities occupy different levels without any change; however, for the highest blockage ratio (66.18%) it means that there is enough space to complete formation of the vortices can decrease the onset of the phenomenon of bistability due to the narrowing of the wake.

Table 2. Statistical characteristics from some cylinders arrangement

Cylinders Diameter (mm)	Mean Velocity (m/s)		Standard Deviation (m/s)	Skewness	Kurtosis
4,5	V1	1,49	1,04	1,09	4,32
	V2	4,45	2,82	0,96	3,32
9,1	V1	1,88	1,37	0,99	3,91
	V2	5,66	3,28	0,88	3,09
15	V1	1,89	1,36	1,06	4,18
	V2	10,73	4,95	0,03	2,04
32	V1	3,25	1,98	0,51	2,73
	V2	4,52	2,87	1,04	3,98

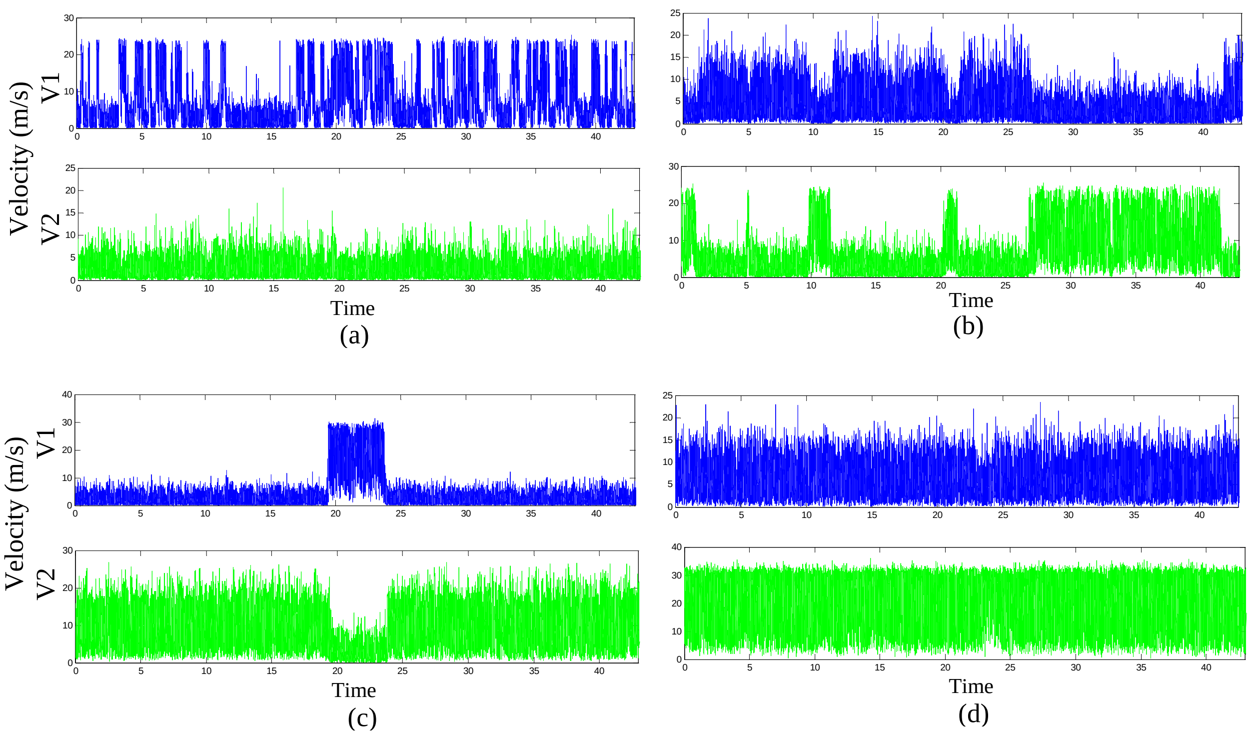


Figure 3. Signal Velocities for cylinders diameter: (a) 25 mm, x/d = 0.338 and Re = 2.28 x 10^4, (b) 40 mm, x/d = 0.295 and Re = 3.54 x 10^4, (c) 50 mm, x/d = 0.25 and Re = 4.26 x 10^4, (d) 60 mm, x/d = 0.628 and Re = 4.81 x 10^4. Probe 1 – V1, Probe 2 – V2.

The discrete wavelet transform shows in Figure 4, the signal reconstruction, held a sort of "attempt" to return. This may be due to high blockage ratio that interfered in order to limit the formation of the wake to prevent that is formed completely and come to develop.

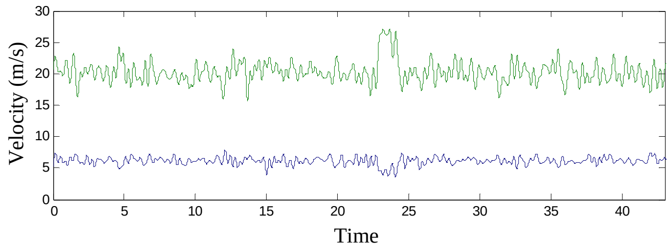


Figure 4. Reconstruction for cylinders diameter 60mm (—— V1) (—— V2).

5.2. Results for p/d = 1.6

Arrangements of cylinder with diameters 4.5, 9.1, 32 and 60 mm showed no characteristic changes of bistability in its levels, for the same reasons argued for the pitch ratio 1.26, i. e., velocities were measured within the wake. In cylinders 4.5, 9.1 and 60 mm, the velocities of each of the signals occupy very different levels. Table 3 presents the statistical characteristics for cylinders of 4.5, 9.1 and 32 mm. The cylinders with 32 mm showed the highest standard deviation.

Table 3. Statistical characteristics from some cylinders arrangements

Cylinders Diameter (mm)	Mean Velocity (m/s)		Standard Deviation (m/s)	Skewness	Kurtosis
4.5	V1	18.65	2.97	-2.63	10.45
	V2	1.69	1.23	2.51	21.64
9.1	V1	18.16	1.63	-3.56	2085
	V2	1.40	1.07	1.23	4.85
32	V1	6.67	4.75	1.35	4.69
	V2	3.25	2.21	1.15	4.48

Changes of velocity levels were observed for other configurations of cylinders of 15, 25, 40 and 50 mm, as shown in Figure 5 and 6. Cylinders of 15 mm diameter showed bistable characteristics with some changes, revealing the importance of positioning of probes to detect the phenomenon. Again, the number of changes is lower for high blockage ratio, in the case of the cylinders with diameters 40 and 50 mm. Reconstructions of the velocity signals via discrete wavelet transform are shown in Figure 7, which shows more clearly the decrease in the number of changes in relation to cylinders of 25 mm.

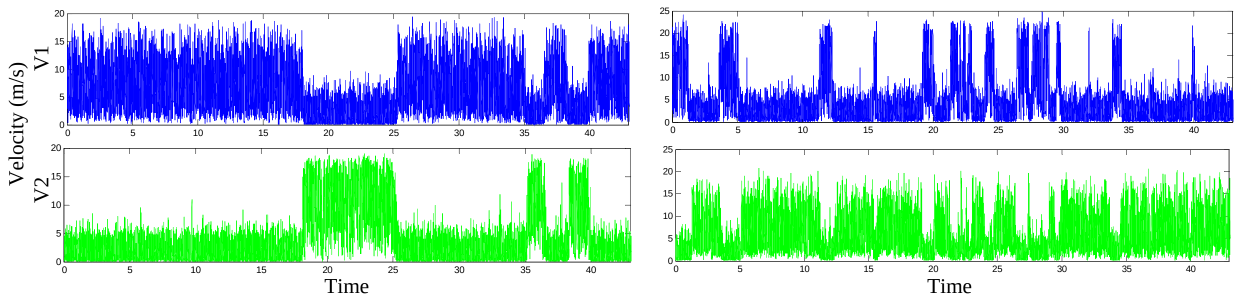
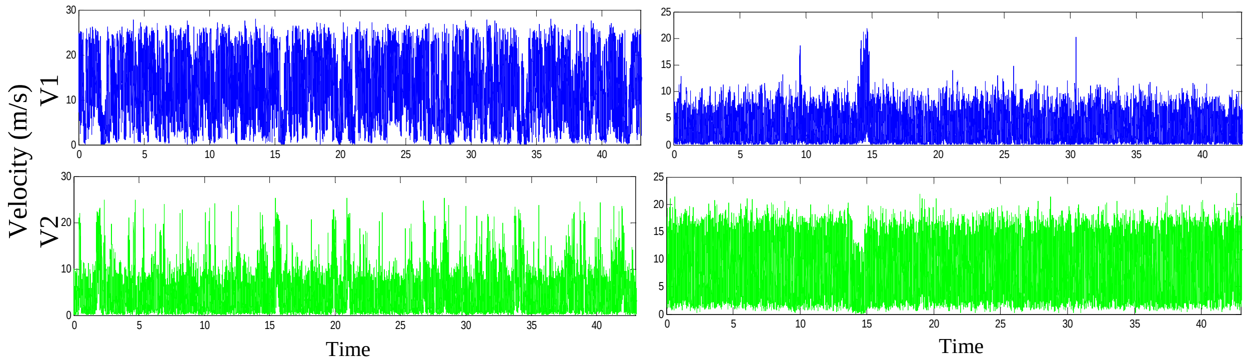
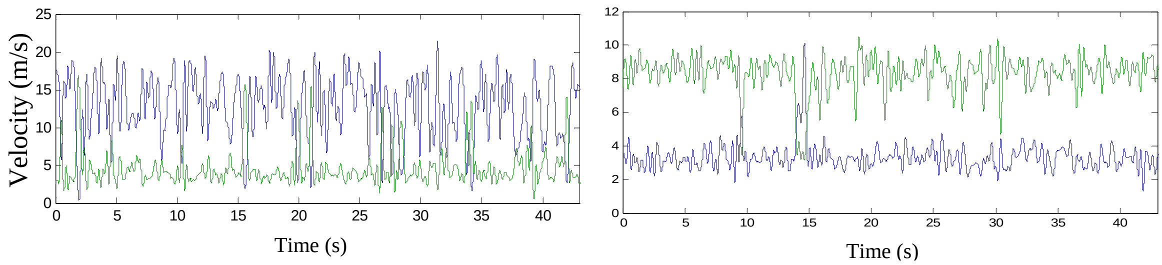


Figure 5. Signal Velocities for cylinders diameter: (a) 15 mm, x/d = 0.733 and Re = 1.56 x 10^4, (b) 25 mm, x/d = 0.28 and Re = 2.63 x 10^4. Probe 1 – V1, Probe 2 – V2.



(a) (b)

Figure 6. Signal Velocities for cylinders diameter: (a) 40 mm, x/d = 0.15 and Re = 4.42 x 10^4, (b) 50 mm, x/d = 0.16 and Re = 5.82 x 10^4. Probe 1 – V1, Probe 2 – V2.



(a) (b)

Figure 7. Reconstruction for cylinders diameter (a) 40 mm and (b) 50 mm (—— V1) (—— V2).

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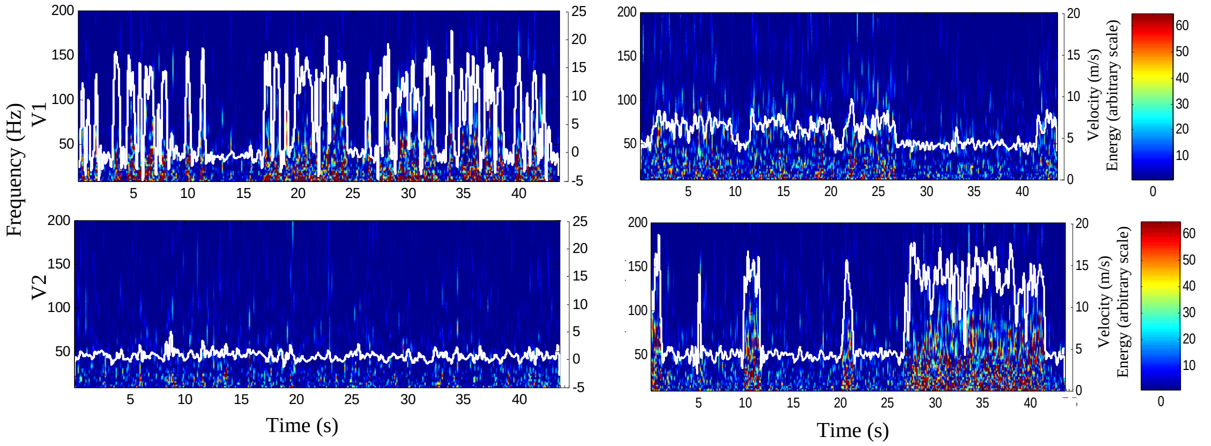
5.3. Spectrograms

The energy distribution of the velocity signals is displayed in spectrograms made from the continuous wavelet transform, Figure 8, 9 and 10. The signals analyzed showed the mode change, characterizing the bistable phenomenon. Reconstructions of the signals processed by discrete wavelet analysis were grouped together with spectrograms. The Wavelet function Db20 level 9 was used, with frequencies between 0 and 2.93 Hz.

The Figure 8 and shows the spectrograms with the reconstruction of the velocity signals for cylinders where the bistable phenomenon for p/d-ratio 1.26 and shows that regions that concentrate more energy are related to higher velocities. Consequently, lower velocities are associated with regions whose energy is lower.



(a) (b)

Figure 8. Spectrograms and reconstruction for signals of cylinders diameter: (a) 25 mm and (b) 40 mm, for p/d = 1.26.

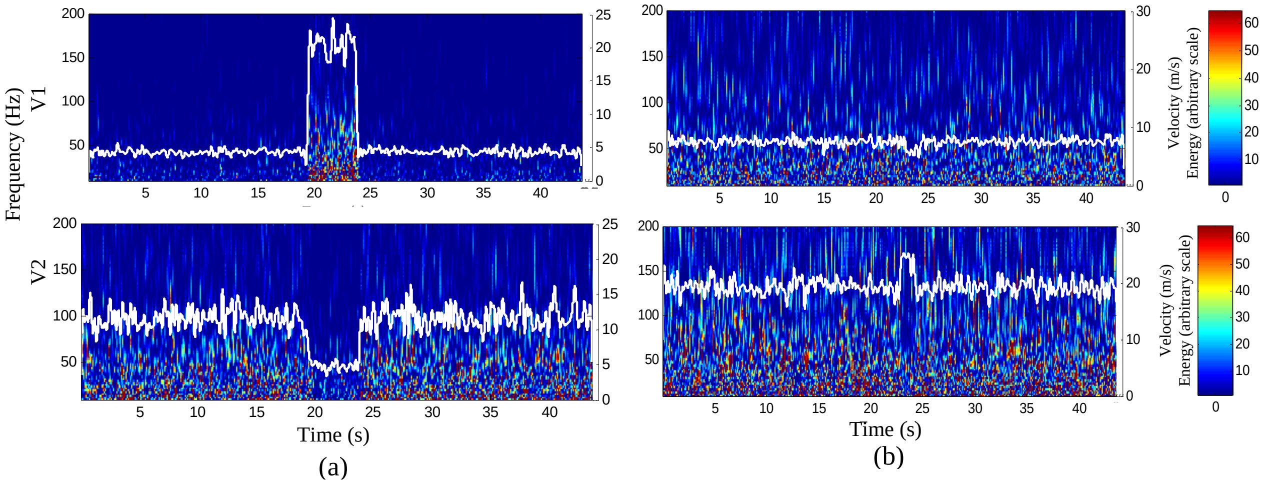


Figure 9. Spectrograms and reconstruction for signals of cylinders diameter: (a) 50 mm and (b) 60 mm, for p/d = 1.26.

Figure 10 shows the spectrograms with the reconstruction of the velocity signals for cylinders where the phenomenon of bistable for p/d = 1.6 is observed. It presents similar characteristics as p/d = 1.26, showing that regions with higher concentrations of energy are related to higher velocity values.

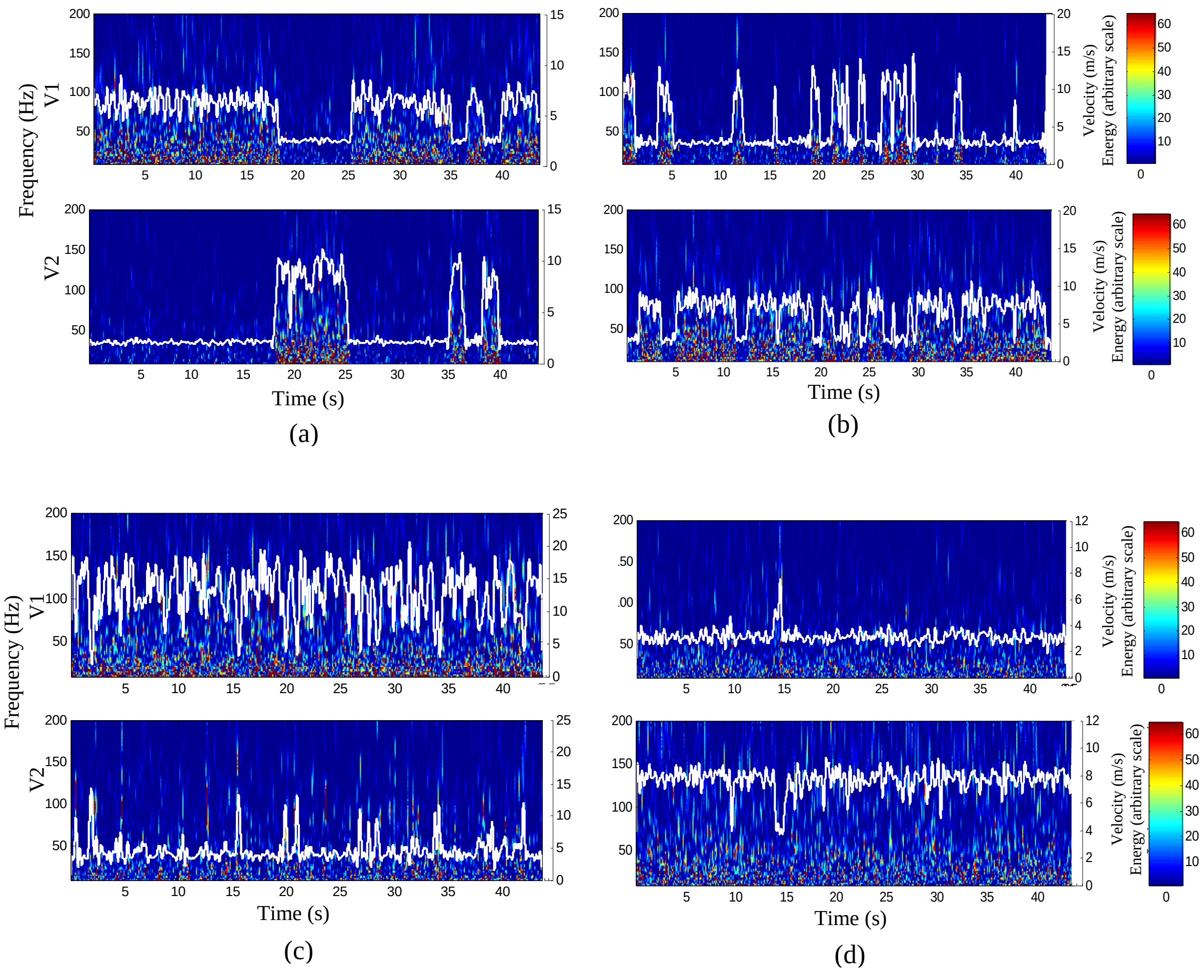


Figure 10. Spectrograms and reconstruction for signals of cylinders diameter: (a) 15 mm, (b) 25 mm, (c) 40 mm and (d) 60 mm, for p/d = 1.6

6. CONCLUSIONS

This paper presents a study on experiments performed on two cylinders subjected to turbulent flow. The effect of blockage ratio on the bistable phenomenon, for two cylinders was studied. In this paper, the blockage ratio was varied through the diameter of the cylinders. The p/d – ratios 1.26 and 1.6. Measurements of the velocity fluctuations in the aerodynamic channel were made using the hot wire anemometry technique. The experiments were performed in the subcritical regime.

For two cylinders, it was realized the strong influence of blockage ratio on the the bistable phenomenon. Smaller cylinders, whose blockage ratios are less than 10% did not present the the bistable phenomenon may come to the conclusion that it can not occur, even with limitations on the dimensions of the probe in front of these tubes, one of the causes of non-captureHowever, for higher blockage ratios, positioning the probe is extremely important in order not to measure velocities within the wake wide. Still, arrangements with more blockage ratios not only presented the phenomenon of bistability, but also seen to decrease it, with the increase of the blockage, with the gradual decrease in the number of exchanges. The extreme case of the cylinder of larger diameter, 60 mm, already has a high blockage ratio that practically covers the bistable phenomenon, which may cause the shedding vortices overlap on the phenomenon. As the blockage ratio is increased, the the bistable phenomenon is decreasing, it was clear to the measurements cylinders 40 and 50 mm.

The bistability was more present in arrays of cylinders with a p/d – ratio 1.6, since the cylinder 15 mm did not show bistable characteristics in the ratio p/d = 1.26 and presented in the blockage ratio 1.6. The great spacing between the cylinders facilitated the positioning of the probe detection is possible in cases like this.

In fact, the blockage ratio, *d/L*, has to be the main measure of flow, since it can cause changes in flow and phenomena that involve, in particular, bistability. The Reynolds number was determined by the velocity value, which was kept constant for all experiments. Therefore its influence was not studied in this experimental work. The influence of the effect of blockage ratio, therefore, becomes more crucial on the bistability.

7. ACKNOWLEDGEMENTS

Authors gratefully acknowledge the support by The National Council for Scientific and Technological Development (CNPq), Ministry of Science and Technology (MCT), Brazil.

Rodrigo S. Silveira thanks CAPES, Ministry of Education, Brazil, also for granting him a fellowship.

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